Sensors & Transducers, Vol. 265, Issue 2, May 2024, pp. 97-105

Sensors & Transducers
Published by IFSA Publishing, S. L., 2024
http://www.sensorsportal.com

Ensuring the Application of Industry 4.0 Design Principles by Using Reference Architectures

[*] Sarah RIEDMANN, Christoph BINDER and Christian NEUREITER
Josef Ressel Center for Dependable System-of-Systems Engineering, Urstein Sued 1,
A-5412 Puch/Salzburg, Austria
Tel.: +43 6801129617
[*] E-mail: sarah.riedmann@fh-salzburg.ac.at

Received: 21 March 2024 / Accepted: 30 April 2024 / Published: 30 May 2024

Abstract: In the context of Industry 4.0, this paper examines the integration of four key design principles – Interconnection, Information Transparency, Decentralized Decisions, and Technical Assistance – into the Reference Architecture Model Industry 4.0 (RAMI 4.0). While RAMI 4.0 offers a robust foundation, its abstract nature hinders practical application. The analysis reveals that RAMI 4.0 partially incorporates the design principles, however because of its abstract nature companies often fail to instantiate it. In an industrial case study of a plastic housing production system, a more specific reference architecture is developed based on RAMI 4.0 which incorporates all30 four design principles more explicitly. The paper underscores the importance of more detailed reference architectures for effective system design in Industry 4.0, offering actionable insights for companies navigating the complexities of this evolving industrial landscape.

Keywords: Reference architecture, Industry 4.0, Reference architecture model 4.0, Model-based systems engineering, Design principles.

1. Introduction

In the era of Industry 4.0, the adoption of design principles plays a pivotal role in shaping the future of industrial systems. This paper explores the integration of four key design principles proposed by Hermann et al. [1] – Interconnection, Information Transparency, Decentralized Decisions, and Technical Assistance – into Industry 4.0 systems during the systems engineering process. In this context, reference architectures, which serve as guideline or blueprint during the systems engineering process, play an increasingly important role. Integrating the design principles into reference architectures reinforces their use when designing industrial systems. While the Reference Architecture Model Industry 4.0 (RAMI 4.0) [2] partially encompasses these principles, this paper aims at investigating the extent of their inclusion and proposes more specific reference architectures to further reinforce these design principles during system design. Moreover, due to the abstract nature of RAMI 4.0 many companies fail to make use of the framework for designing Industry 4.0 systems [3]. Therefore, domain-specific reference architectures may provide a suitable solution to increase the acceptance of RAMI 4.0 and parallelly reinforce the adoption of the four design principles.

This article provides two main contributions. First, an analysis of RAMI 4.0 is conducted, to discern the existing integration of the design principles. This examination serves as a foundation for understanding the strengths and potential gaps within the current framework. Subsequently, the paper presents the development of a specific reference architecture based on RAMI 4.0, with a primary focus on evaluating how the four design principles can be more explicitly incorporated into the architecture. Based on a case study of a plastic housing production system the results are investigated.

The paper concludes with a discussion of the findings, outlining the benefits of adopting more specific reference architectures that explicitly reinforce the use of the design principles proposed by Hermann et al. during system design and at the same provide a blueprint and guideline for the systems engineering process.

2. State of the Art

This section provides an overview over various topics relevant for the research presented in this paper. First the abstract reference architecture model RAMI 4.0 is introduced, followed by a more general definition of reference architectures. Finally, the four Industry 4.0 design principles defined by Hermann et al. are outlined.

2.1. Reference Architecture Model Industry 4.0 (RAMI 4.0)

RAMI 4.0 is an abstract type of reference architecture and provides a framework for systems engineering in an industrial context. The three-dimensional model which encompasses all key facets of Industry 4.0, serves as guideline for categorizing Industry 4.0 technology and illustrating the interconnections within industrial systems. Its primary objective is to establish a shared understanding of Industry 4.0 systems and present diverse stakeholder perspectives. RAMI 4.0 comprises three axes: Hierarchy Levels, Life Cycle & Value Stream, and Layers, shown in Fig. 1. The Hierarchy Levels axis, rooted in IEC 62264 [4], describes various functionalities within a factory. Expanding beyond the layers in the traditional automation pyramid, this axis also includes the layers Product and Connected World, accommodating Internet-of-Things (IoT) elements and thereby reflecting Industry 4.0 systems. Based on IEC 62890 [5], the Life Cycle & Value Stream axis of RAMI 4.0 delineates different states during the development and production phase of production systems and products. Meanwhile, the Layers axis encompasses six interoperability layers, each representing different aspects and features of the system [2, 6].

Despite being standardized in 2016, RAMI 4.0 sees limited adoption among industry companies due to its high level of abstraction.

2.2. Reference Architecture

Reference architectures are defined as collections of knowledge and best practices for developing system architectures in a given context or domain. These architectures serve as both blueprints for new systems and promoters of standardization, thereby enhancing system quality and the architecture development process. To ensure comprehensibility, a shared vocabulary specific to the domain is employed within a reference architecture.

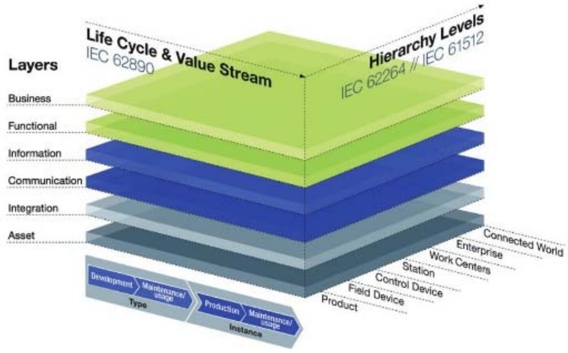

Fig. 1. RAMI 4.0 [6].

Reference architectures can be classified in various ways; it can be distinguished between high and low-level abstraction architectures, domain-specific and non-domain-specific architectures, or single and multi-organization architectures. Reference architectures have been successfully applied in diverse domains, including automotive, avionics, and industrial production plants [7].

2.3. Design Principles Industry 4.0

Hermann et al. [1] have identified four key design principles for Industry 4.0 systems depicted in Fig. 2: Interconnection, Information Transparency, Decentralized Decisions and Technical Assistance.

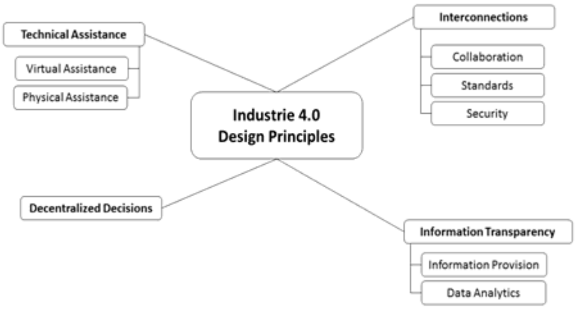

Fig. 2. Industry 4.0 design principles [1].

Interconnection

The concept of Internet of Things (IoT) has evolved into a broader concept known as the Internet of Everything (IoE). This includes aspects such as people, content, ideas, and concepts already encompassed by IoT. Collaboration types vary, involving communication between homogeneous participants (M2M) or between humans and machines (HCI). Common communication standards allow for modularization and form the basis for production in lotsize-1.

Information Transparency

Effective decision-making requires participants in the communication network to have access to contextually relevant information. Information from the virtual and physical world needs to be aggregated to form a meaningful context that can be interpreted by IoE participants via assistance systems.

Decentralized Decisions

Combining Interconnection and Decentralized Decision-Making allows for better decision-making and increases productivity. In the IoE, participants work autonomously, resorting to higher levels only in exceptional circumstances. Cyber-Physical Systems (CPS) with embedded computers enable autonomous monitoring and control of the physical world.

Technical Assistance

To support strategic decision-making Technical Assistance needs to be provided. Assistance systems are crucial for aggregating and visualizing information for informed decision-making. The displayed information needs to be dependable and in time.

3. Approach

The approach for this research involves the use of the iterative method ProSA-RA for the development of a reference architecture. ProSA-RA, with its iterative nature, provides a structured framework for refining and evolving the architecture, ensuring a comprehensive exploration of the design space [8]. Additionally, the theoretical concepts of design science research (DSR) [9] and the agile design science research methodology (ADSRM) [10] were integrated to address the challenges posed by a rapidly changing industrial environment. The agility embedded in the methodology allows for a quick adaptation to emerging trends and facilitates the incorporation of agile methods into the iterative design process.

Basically, both DSR as well as ADSRM suggest the implementation of a case study to obtain a meaningful evaluation. Thus, in the context of this paper, the use case of a plastic housing manufacturer is evaluated and specified in the following. This use case extends our previous work presented in [11] and validates the outcome of our research by ensuring the application of the developed reference architecture and by evaluating the presented findings.

3.1. Case Study & Requirements

In the context of this case study, a smart factory producing plastic housings should be transformed into a flexible production system. To do so, several manufacturing stations are set up, each executing a separate task. To manufacture the plastic housing, a specific process is executed. As the process only allows the production of a single plastic housing at once, this could be compared to an original production line. The original plant consists of a gantry crane with two carriages and four processing stations and a bypass consisting of conveyor belts and turntables. Further workstations represent a milling station, a grinding station, and a specific place for assembly, measurement, and testing. The process is configured in a way that only this single sequence can be run through, but individual workstations can be skipped. At least one of the mentioned workstations must be selected to enable plastic housing production. As far as the process is concerned, a first carriage transports the components from the infeed conveyor to the workstations. Next, a controller automatically determines the most suitable carriage between the respective stations. A second carriage then lifts the component onto the discharge belt, from where it is transferred to a bypass. The bypass transports the component back onto the systems entry belt or discharges it at the last turntable, where the final plastic housing is assembled and tested. To develop a reference architecture considering this case study, the following requirements need to be addressed:

- The original smart factory should be transformed to enable additive manufacturing as well as the configuration and production of individual products. The reference architecture should allow for the selection of the best solutions for individual process steps.
- To ensure the data exchange between different systems, the factory needs to be expanded by a robot and a punching machine, whereby the robot takes over the handling of the components between the punching machine and the bypass. The reference architecture should also consider component interconnections.
- The content of the plastic housing might be chosen flexibly. Different versions of plastic housing bottoms and lids can be manufactured. The reference architecture should support choosing the best fitting specifications.

4. Design Principle Analysis in RAMI 4.0

RAMI 4.0 needs to consider the four Industry 4.0 Design Principles to enable its application for industrial systems engineering. In various proof-of-concept applications model-based systems engineering (MBSE) was used to evaluate how the design principles are addressed by RAMI 4.0. The evaluation is based on several implemented use cases, which have been proposed in the context of previous research projects. This paper analyzes the respective results and subsequently provides a meaningful assessment of how the design principles are addressed by RAMI 4.0.

Interconnection

Interconnection is ensured by modeling the dependencies and traceability of all system elements within the system model or even between complex System of Systems (SoS) [14].

Information Transparency

Information Transparency is ensured by using a model as single point of truth and consistently interconnecting information objects within the Information Layer. The Information Layer of RAMI 4.0 provides a holistic view over all the data accumulated by the system and therefore ensures Information Transparency. However, as outlined by Binder et al. applying the theoretically defined concepts of the RAMI 4.0 Information Layer often fails in real world use cases due to its abstract nature [3].

Decentralized Decisions

Decentralized Decision-Making is ensured by RAMI 4.0 being a Service-oriented-Architecture (SoA) in itself. Especially the Component Layer of RAMI 4.0 deals with service-oriented communication and the interfaces between respective components. Although providing a suitable framework for SoA and thereby allowing for Decentralized Decision-Making in theory, the lack of a detailed specification of the Component Layer hinders its application [12].

Technical Assistance

Technical Assistance is ensured by the RAMI Toolbox, providing a GUI as well as a modeling process description with a step-by-step guideline. The RAMI Toolbox allows for a MBSE systems engineering approach [13].

The findings of the initial analysis reveal that RAMI 4.0 serves as a robust foundation for incorporating the four design principles. To sum up, Information Transparency is achieved through the comprehensive modeling of the information flow between components in the Information Layer and by providing a holistic view of the industrial ecosystem. Decentralized Decision-Making is facilitated by the service-oriented nature of RAMI 4.0.

Technical Assistance, is provided by the RAMI 4.0 Toolbox and Interconnection is achieved by modeling the interconnection of components across various layers.

Although all four design principles are incorporated in principle, the issue when developing a system architecture based on RAMI 4.0 is its abstract nature. RAMI 4.0 lacks the specificity demanded by companies seeking a more tangible, domain-specific blueprint for modeling. To reinforce the use of the four design principles during systems design, a more specific reference architecture is required.

5. Reference Architecture Implementation

This section presents the development of a detailed reference architecture based on RAMI 4.0. Beyond incorporating the design principles in a more detailed manner than RAMI 4.0 alone, the developed reference architecture also aims at being more easily applicable in an industrial context.

The reference architecture model was developed using MBSE, following the ProSA-RA approach. The reference architecture model was developed with the modelling tool Enterprise Architect (EA) and the RAMI 4.0 toolbox Add-In.

Before starting with the development of the reference architecture, its goals and the scope of application were specified. The developed reference architecture shall provide a guideline for the systems engineering process for flexible plastic component production systems. Additionally, the reference architecture should serve as decision aid for choosing the components and assets used for executing the production process. To reinforce the Industry 4.0 design principles during systems design the reference architecture should incorporate the four principles.

To serve as blueprint for a plastic components production system, the abstract production process depicted in the reference architecture contains different work stations for modifying and handling plastic components: a 3D printer and a milling station, for modifying plastic components; a robot and a conveyor belt for transporting goods and a turntable and assembly station for turning and combining individual plastic components to form the assembled products. This abstract production process was modelled across all Interoperability Layers of RAMI 4.0, mainly on the Hierarchy Level Station with some additional information on the Work Center and Control Device Level.

For the reference architecture to serve as decision aid for the components or assets used in the production process, the reference architecture contains multiple solutions for different logical components and functionalities. For transporting plastic components for instance, a robot or a conveyor belt might be used with different benefits and limitations. The functions and requirements the different solutions fulfill are modelled as capabilities in the reference architecture. Every solution has various provided capabilities which fulfill the requirements of the production process to some extent. The required capabilities are formulated and specified during the requirements engineering process together with relevant stakeholders and are added to the model. The provided and required capabilities can then be matched to provide an overview over which capabilities are fulfilled and which solutions might be the best for fulfilling most requirements. In the reference architecture those required and provided capabilities are modelled based on a capability ontology constructed with the Web Ontology Language (OWL), displayed in Fig. 3.

The developed ontology describes the interconnection of capabilities on different abstraction levels and therefore allows to model sub-capabilities and form a capability tree.

The reference architecture is structured in two main parts – a variable and a consistent part. The consistent part contains the logical architecture, while the variable part reflects the technical architecture. Thereby, the reference architecture can be used as blueprint for a new system architecture by building upon the consistent logical architecture. At the same time the variable part of the reference architecture may be used as decision aid by providing some potential technical solutions, modelled on the Asset Layer of RAMI 4.0, with their respective provided capabilities. Moreover, the variable part of the reference architecture might differ between companies or company locations while the consistent part might be used for a whole domain or a number of different companies.

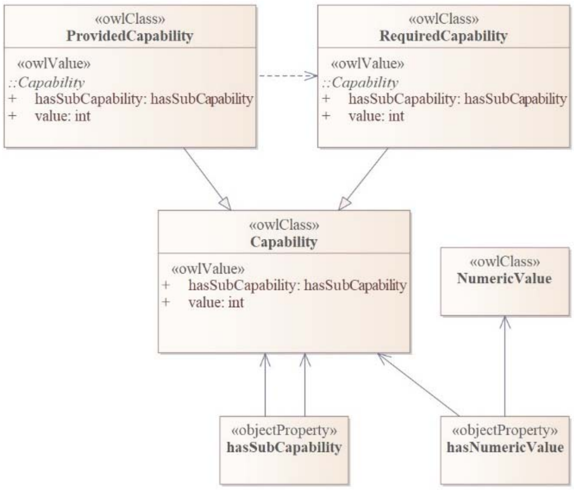

Fig. 3. Capability Ontology.

The following description provides an overview over the RAMI 4.0 layers included in the developed reference architecture on Station Level.

Business Layer

The Business Layer of the reference architecture describes the system context of a plastic component factory. Raw material is delivered to the system of interest and the finished plastic components are passed on to the storage system. Moreover, the Business Layer includes a business case diagram with the identified use case Produce plastic components which is influenced by two business actors, a factory owner and a production line operator. Two requirement diagrams – a business and a functional requirement diagram, include common requirements for plastic component production systems. To give some examples, the performance requirements processing more than X parts per minute and a service time of less than X seconds for instance are included. As for functional requirements the need for a user interface and pick-and-place transportation are modelled as requirements.

Functional Layer

On this layer common functionalities in a plastic component production system are depicted, such as transport, turn, mill, 3D print, punch and assemble. Additionally, input and output of the functions and their interconnection is included on this layer. Moreover, the reference architecture includes the provided capabilities of these functions. The function 3D print provides the capability transform raw plastic into plastic components for instance.

Information Layer

On the Information Layer a common information exchange between logical components, fulfilling the functions defined in the Functional Layer is depicted. For instance, some form of component data is exchanged between logical elements for them to fulfill the desired functionality. The Information Layer of the reference architecture is displayed in Fig. 4.

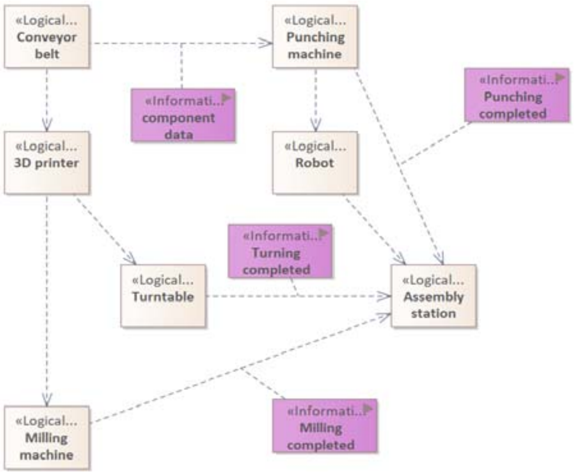

Fig. 4. Information Layer of the Reference Architecture.

Communication Layer

On this layer common interfaces between logical elements are further specified. One such interface is the component delivered interface which is used to notify the respective logical element.

Integration Layer

This layer includes the logical elements fulfilling the functions defined on the Functional Layer. The element 3D printer for instance fulfills the function 3D print and the element Robot fulfills transport and pick-and-place transport.

Asset Layer

The Asset Layer, which is part of the variable part of the reference architecture, includes possible solutions for the logical elements. The assets included in this reference architecture are mainly used for demonstration purposes. Assets are usually company specific and may be further specified in a more detailed reference architecture tailored to specific company needs and constraints for instance. The assets included in this reference architecture are a Prusa 3D printer and a Polyjet 3D printer for instance, which might both be used as logical element 3D printer, depending on the required capabilities defined during the requirements engineering process together with relevant stakeholders. All the assets offer provided capabilities which can be compared to the required capabilities to make decisions on which assets to use for the actual system.

6. Example Application

The proposed contribution is evaluated with a case study dealing with the application and instantiation of a plastic housing system. As previously mentioned, the goal is to transform the currently used linear production system and ensure more flexible plastic housing production by utilizing the reference architecture. As the plant initially has been set up to manufacture cylinder heads, most of this existing system could be reused. However, new functions need to be integrated into this already existing system to produce specific peculiarities of plastic housing. This is done by utilizing the reference architecture and by following the implemented design principles. Thereby, a step-by-step guide is delineated, starting with the context model.

In the context diagram, the system context is modeled by illustrating the surrounding environment of the system and the inputs as well as outputs with connected systems, like the delivered raw material or the finished cylinder heads. After specifying the system context, the black box of the system is addressed. Thereby all processes, including business or manufacturing processes, are modeled. Finally, the requirements and their interdependencies are exhibited in detail.

The next step introduces the specification of every used system function. This includes modeling each function as black- and white-box with all its inputs and outputs. In the functional architecture, the interconnection between the existing functions is depicted, while the white box shows how the respective input is translated into the output. Those functions can be more precisely defined by adding interface information, like data format, data standard or communication protocols. By adding this information, decision-making within the reference architecture is supported, as a more granular selection could be done.

The next step deals with realizing the functions by specifying components. These logical system components carry out those functions and build the base for the technical system architecture. The so-called logical system architecture is an abstract description of the technical implementation and inherits all high-level components. However, this step might be supported by the reference architecture, as important decisions on how functions should be realized can be made. For example, a transport function might be realized by an assembly line, a crane, or a robot, amongst others.

At last, by selecting logical components and modeling them within a logical architecture, the actual real-world solutions implementing the system can be added. This is done by looking into the specification of each component and the previously defined requirements. By making use of the reference architecture, the best solutions can be found. In the context of the chosen case study, the technical architecture is shown in Fig. 5. The image shows that various solutions for a robot or a 3D printer exist. The criteria for selecting a robot are given by the service time and the produced parts per minute, while the 3D printer is chosen based on its availability in different countries. Based on the process requirements, one of the mentioned components might be easily instantiated for a concrete system architecture while at the same time ensuring the Industry 4.0 design principles.

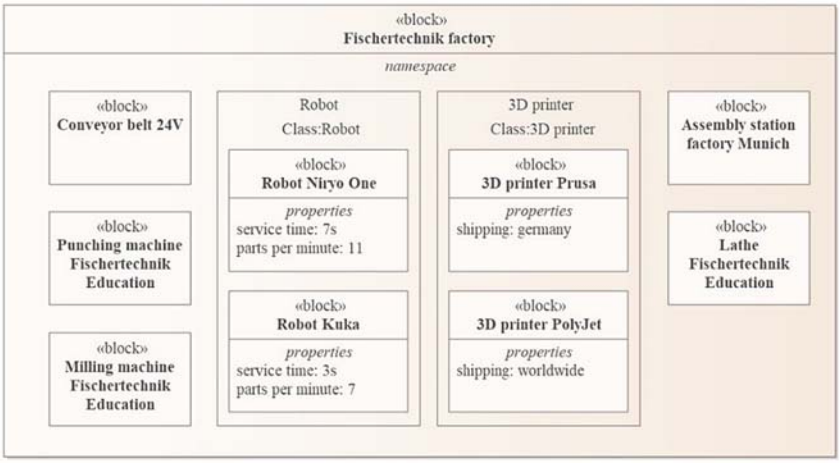

Fig. 5. Case Study technical reference architecture allowing different options for solutions.

7. Discussion

One of the major goals of this paper is to incorporate the Industry 4.0 design principles when developing a detailed reference architecture, which might be used for systems engineering. While the previous section describes the proposed reference architecture and its implementation, this section sums up the results and describes how the design principles are taken into account by the reference architecture.

The individual design principles all fall back to Fig. 6 which shows the traceability between the elements of the reference architecture. On the left-hand side of the image, a short excerpt of the consistent part is displayed by giving examples of a requirement, a function, an interface and an information object of a logical component. The right-hand side indicates the different abstraction levels within the automation pyramid by showing the tree structure and hierarchical dependencies between the system components. These components reach from the production line to the 3D printer, its print controller as well as the user interface and the application programming interface (API). Each of these components might have multiple references to the objects on the left-hand side, which is represented by the traceability of the model. In the following, all design principles refer back to this image.

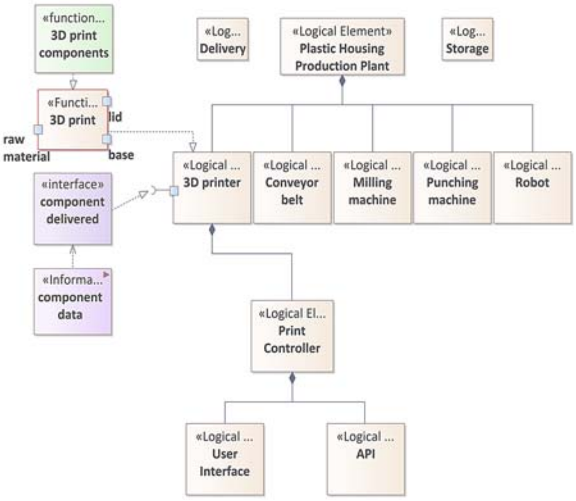

Fig. 6. Traceability Diagram of the Reference Architecture.

Interconnection

The first design principle, Interconnection, is implemented by the model-based characteristic of the reference architecture. The individual components within an actual industrial system, which are interconnected, are also represented by the reference architecture and contain all relationships between each other, like delineated in Fig. 5. By providing an architectural model of the system, the traceability between the components ensures that dependencies between them are complied with. This allows for the stakeholders of the architecture to work on separate parts without impeding each other and at the same time being able to include their results into the overall system due to these dependencies. This interconnection also affects the technical implementation of the individual system based on the reference architecture. By indicating, which IoT or IoE devices are interconnected, those interconnections also need to be established within the ready-to-use industrial system. Another advantage is the enablement of multi-discipline collaboration during the implementation process. For example, functional as well as non-functional capabilities could be addressed independently of each other and various solutions might be deployed simultaneously.

Information Transparency

As far as Information Transparency is concerned, this also falls back to the traceability of the system components within the reference architecture, as shown in Fig. 6. By being consistent throughout the entire model, each component can be traced by the respective information objects. Thereby, decision making is enabled, as each component within the system has access to its information as well as relevant information from connected components that needs to be considered. Additionally, also humans can access this information by tracing the components within the reference architecture. A major advantage of the system model is that not only virtual information is embedded, but also implicit knowledge of various stakeholders and best practices which have evolved through various business processes. By making use of the RAMI 4.0 standardized concepts, the Information Layer is ideal for modeling all the information. Thereby, single information objects might be enriched or processed for optimal use. This means each user or system component has access to consistent information structures and might use this information to make the best possible decisions.

Decentralized Decisions

This design principle is mainly supported by the dependencies and characteristics of RAMI 4.0. Per definition, RAMI 4.0 is a service-oriented architecture (SoA), which implies that each of the system components provides or requires a service. During the production process in runtime each of them needs to decide for itself, if a service is provided or consumed. As the reference architecture contains all interconnections between the components, each component can directly make decisions and choose the communication interface rather than the superior system component. This means, within the reference architecture, this design principle also relies on the other design principles. Interconnection is needed for ensuring a flat hierarchy, Information Transparency is necessary to access relevant information to make decisions and Technical Assistance is required for providing technical support during the decision-making process.

However, the automation pyramid of RAMI 4.0 supports this design principle even further. By providing different abstraction levels, which can be seen in Fig. 6, not only the top component makes the decisions, rather the entire component tree is traced through. During the traversal of the tree, each of the leaves might make a decision of their own and the best possible fit is taken for use. To conclude, this means that Decentralized Decision-Making is implemented in various ways within the reference architecture.

Technical Assistance

Technical Assistance is important for implementing Industry 4.0 scenarios, as systems gain in complexity and enhanced methods are emerging. Thus, to consider this design principle, the proposed reference architecture implements several aspects. Firstly, the architecture itself is provided by EA, which itself comprises of various tools and methods that support the modeling process. By making use of such a well-known software, the entry hurdle of applying the reference architecture to actual industrial projects is reduced. Moreover, an additional Add-In, the so-called RAMI Toolbox, extends EA with additional functionality. This piece of software mainly aims at enhancing the usability and at automating manual or repetitive tasks. By doing so, individual functionalities might be implemented and a variety of different projects might be addressed by offering best possible solutions. This also counts for tasks such as capability matching – i.e., automatically comparing required and provided capabilities. As manually executing this would mean a lot of effort the need for novel methodologies is given. There is a wide variety of possibilities available, such as artificial intelligence (AI) or string comparison. This will be investigated in future projects and subsequently implemented within the RAMI Toolbox.

8. Conclusion

To conclude, the analysis of RAMI 4.0 showed, that the four design principles – Interconnection, Information Transparency, Decentralized Decisions, and Technical Assistance – are incorporated to some extent by the three-dimensional framework. However, the abstract nature of RAMI 4.0 hinders its applicability for real world use cases and thus also the implementation of the design principles. To facilitate the systems engineering process for industrial systems in general and to enforce the use of the design principles, a more detailed reference architecture was developed. This reference architecture builds upon RAMI 4.0 and more explicitly incorporates the design principles, thereby enhancing the system design process as well as system quality.

Further research has to be conducted to evaluate the applicability of the developed reference architecture for more specific use cases. Moreover, the instantiation process of the reference architecture has to be reviewed in detail to evaluate its usability.

Acknowledgements

The support for valuable contributions of Siemens is gratefully acknowledged. The financial support by the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation for Re-search, Technology and Development and the Christian Doppler Research Association as well as the Federal State of Salzburg is gratefully acknowledged.

References

[1]. M. Hermann, T. Pentek, B. Otto, Design principles for Industry 4.0 scenarios, in *Proceedings of the 49th Hawaii International Conference on System Sciences (HICSS'16)*, Hawaii, 5-8 January 2016, pp. 3928-3937.

[2]. M. Hankel, B. Rexroth, The Reference Architectural Model Industrie 4.0 (RAMI 4.0), Tech. Rep., *VDI/VDE Society Measurement and Automatic Control (GMA)*, 2015.

[3]. C. Binder, C. Neureiter, A. Luder, Towards a domain-specific ¨approach enabling tool-supported model-based systems engineering of complex industrial internet-of-things applications, *Systems*, Vol. 9, Issue2, 2021, 21.

[4]. IEC 62264: Enterprise control system integration, *International Electrotechnical Commission*, 2016.

[5]. IEC 62890: Life-cycle management for systems and products used in industrial-process measurement, control and automation, *International Electrotechnical Commission*, 2016.

[6]. Umsetzungsstrategie Industrie 4.0: Ergebnisbericht der Plattform Industrie 4.0, Berlin, Frankfurt am Main, Tech. Rep., *Bitkom, VDMA, and ZVEI*, 2015.

[7]. E. Y. Nakagawa, P. Oliveira Antonino, Reference Architectures for Critical Domains, *Springer International Publishing*, 2023.

[8]. E. Y. Nakagawa, M. Guessi, J. C. Maldonado, D. Feitosa, F. Oquendo, Consolidating a process for the design, representation, and evaluation of reference architectures, in *Proceedings of* the *IEEE/IFIP Conference on Software Architecture,* Trondheim, 2-4 June 2014, pp. 143-152.

[9]. A. Hevner, S. Chatterjee, Design Science Research in Information Systems, *Springer US*, Boston, MA, 2010, pp. 9-22.

[10]. K. Conboy, R. Gleasure, E. Cullina, Agile design science research, in New Horizons in Design Science: Broadening the Research Agenda, *Springer International Publishing*, 2015, pp. 168-180.

[11]. S. Riedmann, C. Binder, C. Neureiter, Incorporating design principles in industry 4.0 system architecture using reference architectures, in *Proceedings of the 4th IFSA Winter Conference on Automation, Robotics & Communications for Industry 4.0/5.0 (ARCI' 2024)*, Innsbruck, Austria, 7-9 February 2024, pp. 295-300.

[12]. C. Binder, G. Lastro, C. Neureiter, A. Luder, Enabling model-based engineering of service-oriented architectures within complex industrial systems, in *Proceedings of the IEEE International Symposium on Systems Engineering (ISSE'21)*, Vienna, 13 September-13 October 2021, pp. 1-6.

[13]. C. Binder, A. Cala, J. Vollmar, C. Neureiter, A. Lüder, Model-driven engineering of flexible production systems with the rami toolbox, in *Proceedings of the IEEE 21st International Conference on Industrial Informatics (INDIN'23)*, Lemgo, 17-20 July 2023, pp. 1-8.

[14]. C. Binder, B. Brankovic, C. Neureiter, A. Lüder, Lessons learned from developing industrial applications according to rami 4.0 by applying model based systems engineering, in *Proceedings of the 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA'20)*, Vienna, 8-11 September 2020, pp. 883-888.

USTI-
EXT